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Drivers of long-term carbon dynamics in cropland: A bio-political history (France, 1852–2014)

Julia Le Noë[a,b,*], Gilles Billen[a], Bruno Mary[c], Josette Garnier[a]

[a] Sorbonne Université, CNRS, EPHE, UMR 7619 METIS, 4 place Jussieu, Box 105, 75005, Paris, France
[b] Institute of Social Ecology (SEC), Department of Economics and Social Sciences, University of Natural Resources and Life Sciences, Wien, Austria
[c] INRA, UR Agroimpact, Pôle du Griffon 180, rue Pierre-Gilles de Gennes, 02000, Barenton-Bugny, France

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ABSTRACT

Following the COP 21, it has been widely recognized that agricultural soils may contribute toward mitigating or enhancing climate change depending on their behavior as a sink or a source of carbon (C) to the atmosphere. Here, we studied the case of soil organic carbon (SOC) stocks in French cropland at the regional scale from 1852 to 2014 by coupling the GRAFS approach (Generalized Representation of Agro-Food System) with the AMG model (after its authors names: Andriulo, Mary, Guérif). Our results emphasize the role of crop net primary production (NPP) as the main driver of changes in SOC stocks through the input of crop residues. Three distinct phases of NPP were identified: (1) from 1852 to 1950, a slow rise in NPP occurred, which induced a moderate increase of cropland SOC pools (1–2‰ yr^{-1}); (2) from 1950 to 1980, NPP increased considerably, resulting in a much higher rate of SOC accumulation (2–4‰ yr^{-1}); (3) from 1980 to 2014, divergent trajectories were followed according to regions with either a slowdown in NPP growth with moderate increase in SOC stocks (0–2‰ yr^{-1}), or a reversed trend toward declining NPP induced by a reduction of fodder production, replaced by imported feed which led to negative change of cropland SOC stocks. We highlight that these evolutions of carbon dynamics in cropland were closely linked to changes in the French social political context, from the second Empire to the Cold War and the advent of a neo-liberal era.

As a whole, for France, we found a rate of C sequestration in the top 30 cm of cropland soils of about 1.7 Mt C yr^{-1} for the last two decades, less than one fifth of the current fossil-fuel-based CO_2 emission rate of the French agricultural sector which exceeds 8 Mt C yr^{-1}. Our study showed that in developed countries like France, where a sharp increase in cropland SOC stocks occurred owing to the modernization of agriculture, this should be considered as a "fossil-fuel-powered carbon sink", which does only partly compensate for the direct emissions through mechanization and fertilizer production that induced it.

1. Introduction

Carbon (C) storage in arable soil is a key feature of both fertility and greenhouse gas balance and was recently promoted through the 4‰ initiative (http://www.4p1000.org/; Minasny et al., 2017) aiming at improving farming practices so as to increase soil C sequestration as a way to offset anthropogenic CO_2 emission. The balance between fresh organic matter inputs and mineralization of soil C defines soil as a sink or source of C. This balance results from complex soil processes depending on many variables at the field scale such as pedo-climatic conditions (Kätterer et al., 1998; Saffih-Hdadi and Mary, 2008; Milesi Delaye et al., 2013; Stockmann et al., 2013), soil aggregation (Six et al., 2000; Puget et al., 2000; Haynes, 2000; Bronick and Lal, 2004), micro-organism activities (Anderson and Domsch, 1989; Sparling, 1992; Six et al., 2006; Miltner et al., 2012), land-use change (Conant et al., 2001; Lal, 2004; Stockmann et al., 2013), as well as the nature and quantity of C inputs (Campbell et al., 1991; Kong et al., 2005; Poeplau and Don, 2012; Autret et al., 2016). Recent studies (Sleutel et al., 2006; Bertora et al., 2009; Virto et al., 2012; Autret et al., 2016; Poulton et al., 2018) have shown that, among all these factors, the quantity and nature of C inputs are the most determinant for the storage or release of soil C in the absence of land-use change. The nature and quantity of C inputs to cropland are themselves determined by crop rotation (Campbell et al., 1991; Autret et al., 2016), crop productivity, and manure application (Jenkinson and Rayner, 1977; Sleutel et al., 2007). This, in turn, depends on agricultural practices such as tillage (Virto et al., 2012), irrigation, and fertilization (Burney et al., 2010; Mueller et al., 2012), which are driven by the structural organization of agricultural

* Corresponding author. Present address: Institut für Soziale Ökologie (SEC), Schottenfeldgasse 29, 1070, Wien, Austria.
E-mail address: julia.lenoe@boku.ac.at (J. Le Noë).

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production at various spatial scales (Gingrich et al., 2015; Aguilera et al., 2018). Agricultural production must indeed be considered an important economic sector, conditioning in the first instance the development of all other sectors while its structural characteristics are in turn affected by its integration into the market economy (Erb et al., 2008; Krausmann et al., 2012).

In this context, an analysis of the C storage trend in agricultural soil by taking a historical and regional perspective is needed. To our knowledge, only one study (Aguilera et al., 2018) has focused on the interrelation between C storage in agricultural soil and the socio-ecological metabolism of agro-food systems. This study was conducted for Spain at the national scale for the period 1900–2008, considering Spain as a model for Mediterranean countries. The authors reported that the history of Spanish agriculture has been marked by the long period of isolationism under the fascist regime (1936–1978), which strongly impacted crop productivity and net primary production (NPP) and consequently the C inputs into soils. The case of French regions, having a wide range of climates, agricultural management practices, and food production trajectories (Le Noë et al., 2018), is of particular interest with respect to soil C storage. Furthermore, France is currently among the largest agricultural countries in Europe, being the first exporter of cereals (FAO, 2017); in addition, France can be considered a model for temperate countries, with the exception of South-East France, which experiences a Mediterranean climate.

The aim of our study is to assess the evolution of C stocks in cropland in the 33 French territories defined by Le Noë et al. (2016) over the period 1852–2014. To this end, we coupled the GRAFS model (Generalized Representation of Agro-Food System; Billen et al., 2014; Le Noë et al., 2017) to the AMG model (after its authors names: Andriulo, Mary, Guérif; Saffih-Hdadi and Mary, 2008; Milesi Delaye et al., 2013; Clivot et al., 2019). The GRAFS model offers a representation of the agro-food system from the angle of nutrient and C flows, which enables one to highlight the interrelations between the structure of the agro-food system, agronomic performances such as grain yield and NPP, and environmental impacts related to C inputs into soil. AMG is a simple mechanistic model estimating soil C balance from C inputs and outputs. It considers three pools of organic C: fresh inputs as well as a labile and an inert stock of soil C. For our application to the long-term regional chronicle, C inputs are provided from the GRAFS model and C outputs are calculated based on mineralization coefficients of labile soil C estimated as a function of basic soil properties. Our study seeks to answer three related questions: (1) How did the soil organic C (SOC) in cropland change over the studied period? (2) Which were the main levers responsible for the observed trends of cropland SOC? (3) Given the past and current trends, would the objective of a 4‰ yr^{-1} accumulation rate of C in cropland soil be achievable?

2. Material and methods

2.1. Principles of the method

Coupling the GRAFS approach with the AMG model enables us to derive a direct link between the structure of agro-food systems, dominant crops cultivated, pedo-climatic conditions, and the soil C dynamics in cropland (Fig. 1). Both models have been extensively described in previous studies (GRAFS: Le Noë et al., 2017, 2018; AMG: Saffih-Hdadi and Mary, 2008; Clivot et al., 2019). Therefore, here we only provide a synthetic description of the main hypotheses and data sources used to establish NPP, humified C inputs to soil, mineralization rates of labile C in soil, and SOC changes during the period by coupling the two models. Although the AMG model does not account for any microbial pool, and more generally is based on a simplified and semi-empirical representation of the complex processes involved in soil organic matter dynamics, Saffih-Hdadi and Mary (2008) demonstrated that the AMG model provides results similar to those more sophisticated model considering a microbial pool when simulating the level of SOC stocks under controlled long term experiments.

The focus of this study is on cropland (including temporary grasslands that are part of crop rotations) for which the AMG model was initially developed and calibrated. However, we also calculated the evolution of SOC in permanent grassland in order to account for the possible shift in SOC related to the conversion of permanent grassland into cropland. We applied the GRAFS approach for 22 dates from 1852 to 2014 to the 33 structurally homogeneous regions defined by Le Noë et al. (2016), and interpolated the humified C inputs between the two closest documented dates for each region.

2.2. Net primary production

In order to estimate cropland NPP for the 35 different types of crops considered in GRAFS (see supplementary material, S1), we used the harvested production reported by Agreste (2017) for the period 1970–2014 and by non-digitized official registers (available from *Gallica.bnf.fr*) for earlier periods (these data are available at the regional level for the period 1852–2014 in Le Noë et al., 2018), and applied the approach reported by Bolinder et al. (2007) to derive NPP. Briefly, Bolinder's approach considers four plant parts: the harvested product, the above-ground residues, the root residues, and the extra-root residues. Because of significant uncertainties regarding below-ground biomass production, we modified this approach slightly. Indeed, Bolinder considered a fixed shoot–root ratio, while recent studies show that root C inputs are independent of above-ground production and can be better estimated using a constant crop-specific value (Taghizadeh-Toosi et al., 2016; Hirte et al., 2017; Hu et al., 2018). To estimate this constant below-ground production, we first used the crop relative C allocation coefficients provided by Bolinder et al. (2007) to calculate root biomass production for each crop in each region over the whole study period. We subsequently derived an average root dry biomass production per hectare specific to each crop for each region over the whole period. We also did not account for extra-root residues because of the large variability and uncertainty existing in the literature regarding the quantification of rhizodeposition (Domanski et al., 2001; Bolinder et al., 2007; Pausch and Kuzyakov, 2018). The effect of our new approach for underground biomass production estimation was tested via a sensitivity analysis. Finally, the NPP in each region was calculated over the whole study period by using (1) the crop-specific relative C allocation coefficients to estimate above-ground production and (2) the calculated root biomass production, applying the following equation:

$$NPP_{i,j} = S_{i,j} \times [Y_{i,j} \times (1 - W_i) \times 0.44/HI_i + 0.40 \times Y_{ri,j} \times (1 - \beta_i^h)]$$

where $NPP_{i,j}$ denotes the NPP in region j of crop i (t C); $S_{i,j}$ is the surface dedicated to crop i (ha); $Y_{i,j}$ is the yield of the crop (t fresh weight ha^{-1}); W_i is the moisture content of harvested product; 0.44 is the C content in dry matter of the aerial biomass; HI_i is the crop harvest index; 0.40 is the C content in dry matter of root; $Y_{ri,j}$ is the calculated average root biomass production for crop i in region j (t dry weight ha^{-1}), and β_i^h is a coefficient relative to root distribution (Fan et al., 2016) that enables us to account for root residues down to depth h. For cereals, HI is calculated as a linear function of crop yield following the Fan method (Fan et al., 2017) with the intercept and the slope being specific for each species. For all other crops, HI is calculated as the ratio of relative C allocation in above-ground residue to the sum of relative C allocation in harvested crop and above-ground residues.

Dry biomass production of weeds in historical periods was taken into account in cropland NPP using data from modern weed production without pesticide. Further details on NPP estimation are provided in S1.

2.3. Humified C inputs

Above-ground and below-ground annual plant residue inputs to cropland and permanent grassland were calculated as NPP minus

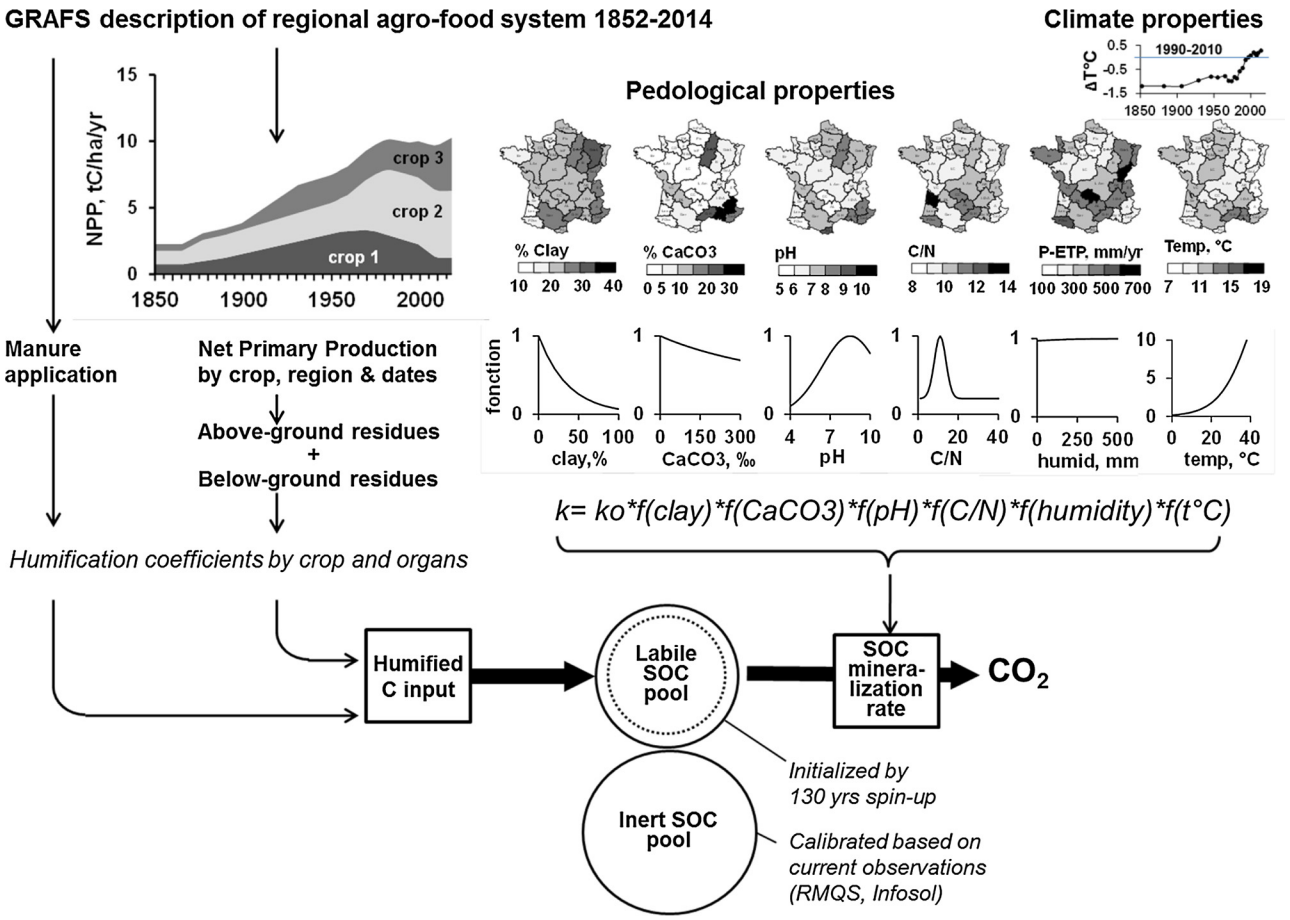

Fig. 1. Coupling of the GRAFS and AMG models. The AMG model considers three pools of C: fresh organic C inputs as well as soil labile organic C and inert soil organic C. Humified C inputs to the soil are estimated from the GRAFS considering three main types of inputs: manure, above-ground residues, and below-ground residues. The balance between annual humified C input and output via labile SOC mineralization drives the change in total SOC pool of cropland in the absence of land-use change. The SOC mineralization rate (k) is considered as the product of individual function of pedo-climatic variables including clay and carbonate content, pH, C:N ratio, humidity and temperature; these functions are illustrated in the small diagrams; the maps illustrate the geographical distribution of these pedo-climatic variables.

harvested crops and straw exportation reported in agricultural production statistics. For permanent grassland, we assumed that the reported herbaceous production corresponds to grass mowed or grazed by cattle. Humified C inputs from plant residue inputs were subsequently calculated using humification coefficients specific to plant, above-ground, and below-ground inputs as described by Clivot et al. (2019) and Justes et al. (2009) for the STICS model. Other soil C inputs included manure and urban sludges. For manure inputs we applied the same procedure as described by Le Noë et al. (2018). In short, nitrogen excretion rates for current (CORPEN, 1999; MATE, 2002; CITEPA, 2013) and past periods (Bertin, 1856; Girardin, 1876; Gueymard, 1868; Gros, 1957; Noirfalise, 1974) are known or estimated for the 39 livestock categories considered here. The partition of excreta between cropland and permanent grassland for each animal category and region has been documented for the current period by Le Noë et al. (2017) based on CGDD (2013). For historical periods, the partition between cropland and grassland was estimated following hypothesis based on historical literature (Le Noë et al., 2018). Finally, C inputs to cropland and permanent grassland were estimated based on C:N ratios of animal excretion after N volatilization has occurred as provided by MEEM (2010) and Soltner (2005). The humification rates of these inputs were taken from Bertora et al. (2009) and Clivot et al. (2019).

Recycling of C from human excreta was assumed to occur only on cropland and was calculated based on an estimated rate of human waste recycling, differing for urban and rural populations, and varying regionally and throughout the whole period, based on several sources (Paulet, 1853; Liger, 1875; Girardin, 1876; Barles, 2005; National surveys of INSEE and the Ministry in charge of sanitation, Goubert, 1984; Bellanger, 2010). The procedure and hypothesis involved have been explained in detail by Esculier (2018).

2.4. Mineralization of labile C

The mineralization rate k (yr^{-1}) of labile C stock was calculated according to Clivot et al. (2017) using the following equation:

$$k = k_o \times f_1(C) \times f_2(CaCO_3) \times f_3(T) \times f_4(pH) \times f_5(H) \times f_6(C/N)$$

where k_0 is the potential mineralization rate (yr^{-1}); C is the soil clay content (g kg^{-1}); $CaCO_3$ is the soil carbonate content (g kg^{-1}); T is the mean annual temperature (°C); H is the water balance defined as rainfall – potential evapotranspiration + irrigation (mm yr^{-1}); C/N is the carbon to nitrogen ratio (g g^{-1}) of bulk soil organic matter (see S1 for further details on equations). These functions were calibrated using a dataset of field experiments with varying climate conditions typical of the diverse French regions. In the present study, except for temperature, we used these functions to estimate average mineralization rates of labile C in cropland and grassland soils at the regional level from the corresponding regional average value of the soil variables (see below), which is an approximation due to the nonlinearity of the functions.

Average clay content in cropland and permanent grassland was calculated by superimposing GIS layers of land use (CORINNE LandCover, www.data.gouv.fr/fr/datasets/), French 'départements'

(Nuts 3) and clay content in the 20-cm topsoil (European Soil Data Center, Ballabio et al., 2016). Clay content in cropland and permanent grassland for each region was subsequently calculated as the average clay content of each department included in a given territory weighted by surfaces of cropland and permanent grassland. The clay content was assumed to be constant over the whole period studied.

Because of the highly nonlinear character of the $f_3(T)$ function, its annual mean value was calculated for each 'département' as: $f_3(T) = \sum_i^n f_3(T_i)/365$, where Ti is the daily mean temperature and i is the Julian day. The seasonal pattern of Ti variations was calculated from daily temperature data at the 'département' level from 1990 to 2010, taken from the MESAN database (Raimonet et al., 2017). In order to take into account the effect of climate change over the period 1852–2014, we superimposed to the latter daily data a temperature shift calculated for each region and each year as the annual mean temperature deviation from the 1990–2010 average, obtained from long-term annual mean data per department available from 1950 to 2014 (E-OBS, www.ecad.eu/download/ensembles/download.php) and completed by the national data of Moisselin et al. (2002) for the period 1850–1950.

The average water balance (i.e., rainfall – evapotranspiration) was estimated from the values of specific total runoff obtained for the last two decades at the 'département' scale from the HYDRO data bank (hydro.eaufrance.fr/). We used these values for the whole study period for both cropland and permanent grassland. Carbonate content, C/N ratio, and pH in the 30-cm topsoil were estimated using the data collected by the Network of Measurements and Quality of Soil (RMQS, www.gissol.fr/tag/rmqs), implemented by INRA.

Carbon losses through erosion could also represent an output of C from cropland but were not accounted for in this study. Changes of SOC stocks due to erosion are difficult to evaluate because erosion is likely to engender both output through losses and input through redeposition. Integrating all C fluxes for European Union agricultural soils, Lugato et al. (2016) calculated that the net effect of erosion on agricultural soils can be either positive or negative on the overall soil C balance.

2.5. Changes in soil organic carbon

Changes in labile C stocks in the 30-cm topsoil of cropland and grassland of each territory were calculated by incrementation on an annual time-step. Labile C stocks were initialized by a spin-up procedure assuming constant rates of humified C inputs during a period of 130 years prior to 1852. The land-use change that may have occurred from permanent grassland to cropland was calculated from 1852 to 2014 if, for a given year, permanent grassland lost areas while cropland gained surfaces, considering the conversion from one to the other as the smallest absolute area change. The process was iterated each year to calculate stocks of labile C in permanent grassland and cropland for each year and region (see S1 for further details on calculation).

Stocks of inert C were estimated for 2014 by subtracting the calculated stocks of labile C from the observed total stocks of C. These total stocks of C in cropland were obtained from the RMQS database mentioned earlier, and aggregated at the territorial level. We assumed that for a given region the stock of inert C was the same for permanent grassland and cropland and did not change over the studied period, even during conversion of crop to grassland.

2.6. Uncertainties

Uncertainties were estimated applying the Monte Carlo method to generate random samples of values for humified C inputs to cropland, current SOC stocks in the 30-cm topsoil, and for each variable of the mineralization coefficient, considering their own level of uncertainty, which can differ over the time period covered by the study. On the basis of a previous study (Le Noë et al., 2017), we estimated that relative uncertainties on humified inputs varied between 10 and 20% with the highest uncertainty level being associated with the oldest periods. For pedoclimatic variables, we assumed relative uncertainties to vary between 10% for temperature to 15% for clay content. The intermediate variables (such as mineralization coefficient) and output variables (such as SOC stocks) were computed according to the Monte Carlo simulation of the primary data (Loucks et al., 2005). We thus generated a distribution of the main variables and outputs of the model by bootstrapping the Monte Carlo simulation with replacements (1000 replicates). The uncertainty for each variable and parameter was given by the standard error of the mean of the 1000 replicates.

A sensitivity analysis was also performed to test the effect of modifying key parameters on the results. The tested parameters were weed biomass (one exploration with no weed), manure input (one exploration with no manure), temperature (one exploration assuming constant T value since 1852), root–shoot ratio (one exploration with constant root–shoot ratio instead of fixed root C biomass production per hectare), and land-use change (one exploration without considering land-use change). To evaluate the importance of each parameter, the analysis was performed at the territorial level and at the national scale by pooling together all territories.

3. Results

3.1. Changes in net primary production

Overall, cropland NPP (t C ha^{-1} yr^{-1}) increased in all regions until the beginning of the 1980s. Contrary to the observation of Aguilera et al. (2018) for Spain, we found a rather limited contribution of weeds to cropland NPP, representing 4.2%, 2.5%, and 0.1% in 1852, 1955, and 2014, respectively. Fig. 2 shows the evolution of NPP in six typical French territories characterized by contrasted pedo-climatic conditions and agricultural trajectories: Eure-et-Loire, Manche, Brittany, Loire Amont, and Aveyron-Lozère. Similar data for all other regions and for France are provided in S2.

NPP increased slightly in all regions from 1852 to the beginning of the 1950s with, however, a small decrease during the Second World War (Fig. 2 and S2). Crop rotations were dominated by cereals, temporary grassland and fodder in all regions, but in some regions such as Nord Pas-de-Calais, Picardie, and Ile-de-France, roots and tubers also occupied a significant share.

A sharp growth in NPP occurred in the following 30 years (1950–1980), reaching a peak in some regions in the 1980s. This coincided with an increased reliance on N and P mineral fertilizers (Fig. 3e, f), which boosted productivity. Crop rotations diversified with roots and tubers being given more place in almost all regions and the emergence of protein crops and oil-seed crops. However, in most regions, the NPP of crop rotations remained dominated by cereals (e.g. Eure-et-Loire and Landes) or temporary grassland and fodder (e.g. Manche, Brittany, Aveyron-Lozère). In the regions where temporary grassland and fodder became the main crops, livestock density increased too (Fig. 3b).

From the 1980s to 2014, there were contrasting trends in cropland NPP. Some territories presented stagnating NPP (e.g. Loire Amont, see Fig. 2); some showed decreasing NPP (e.g. Manche and Brittany) while others still had increasing NPP (e.g. Eure-et-Loire, Aveyron-Lozère). For France as a whole, the dominant trend for the last period was stagnating NPP (see S2). The main characteristic of the last 30 years is the regression of temporary grassland and fodder NPP in almost all territories, including those where livestock density was still increasing, occasionally reaching very high values (e.g. Brittany and Manche). This was often accompanied by an increased feed importation from abroad in several regions (Fig. 3a). Brittany and Loire Aval represent emblematic examples of this type of trajectory. The same trend was also visible for all France. However, territories such as Eure-et-Loire and Picardy also presented a decrease in temporary grassland and fodder NPP, together with the virtual elimination of livestock production

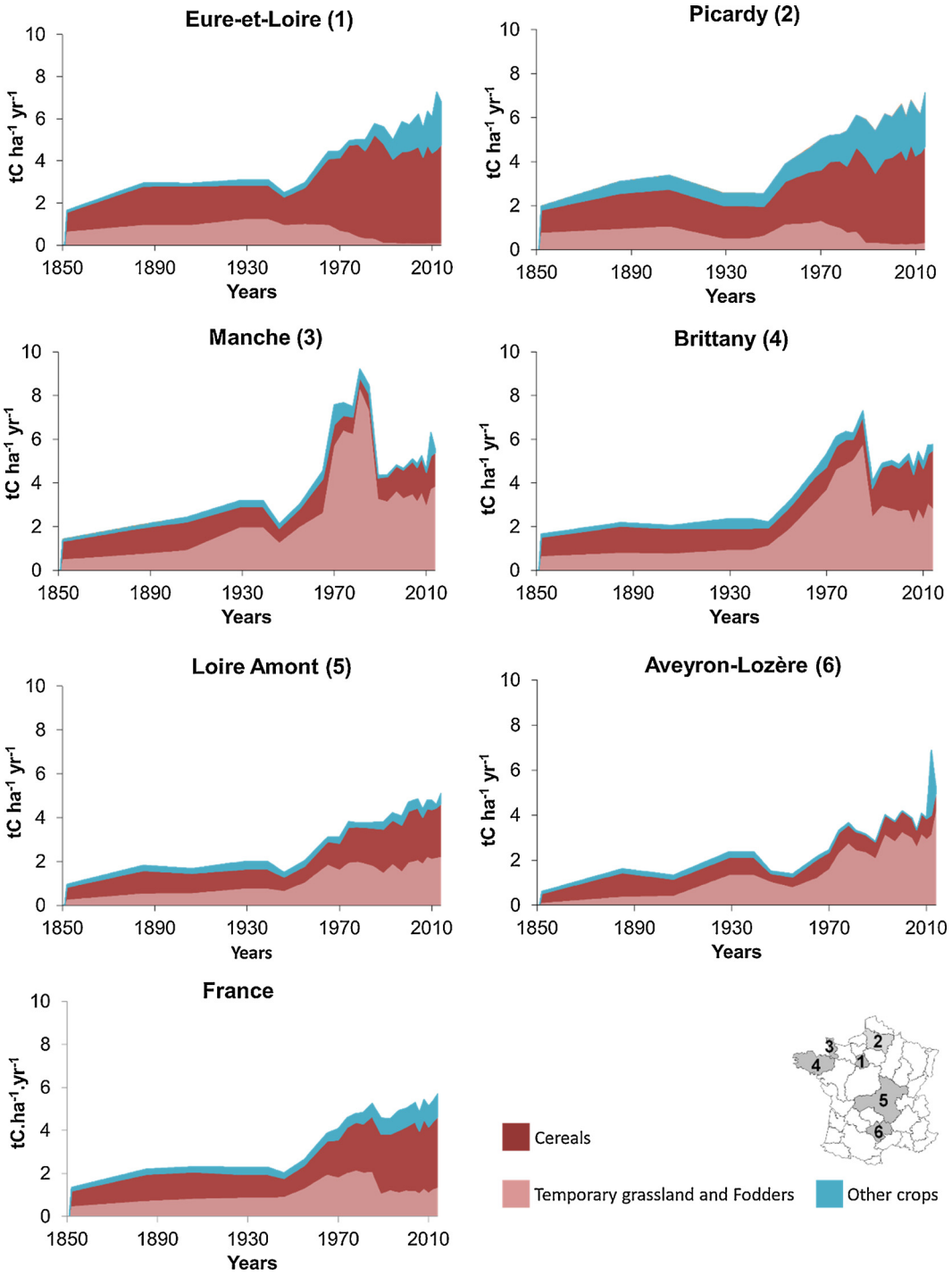

Fig. 2. Changes in cropland NPP from 1852 to 2014 in six typical French territories: Eure-et-Loire, Picardy, Manche, Brittany, Loire Amont, and Aveyron-Lozère, distinguishing NPP for eight crop categories.

(Fig. 3b) and an ever-increasing NPP in cereals, roots, and tubers. Some territories did not show any decrease, neither in temporary grassland and fodder NPP nor in livestock density (e.g. Loire Amont see Figs. 2 and 3b). This type of territory was previously described (Le Noë et al., 2017, 2018) as an integrated crop and livestock farming system with better nutrient recycling at the territorial level.

3.2. Evolution of humified C inputs

The changes in humified C inputs to cropland (Fig. 4 and S2) basically followed those of NPP, since in three quarters of territories the contribution of humified C inputs through manure was less than 28%, 39%, and 35% in 1852, 1955, and 2014, respectively, with some exceptions as in Cantal-Corrèze where manure represented 59%, 60%, and 61% of total humified C inputs in 1852, 1955, and 2014, respectively. Overall, the relative importance of manure decreased over the period of 1955–2014 (Fig. 4) although absolute inputs increased concomitantly with livestock density (Fig. 3b), reflecting the fact that crop productivity increased faster than manure application in this period.

As for NPP, humified C inputs to cropland rose slowly from 1852 to the beginning of the 1950s. From 1950 to 1980, C inputs increased sharply, whereas in the last period, from 1980 to the present, the

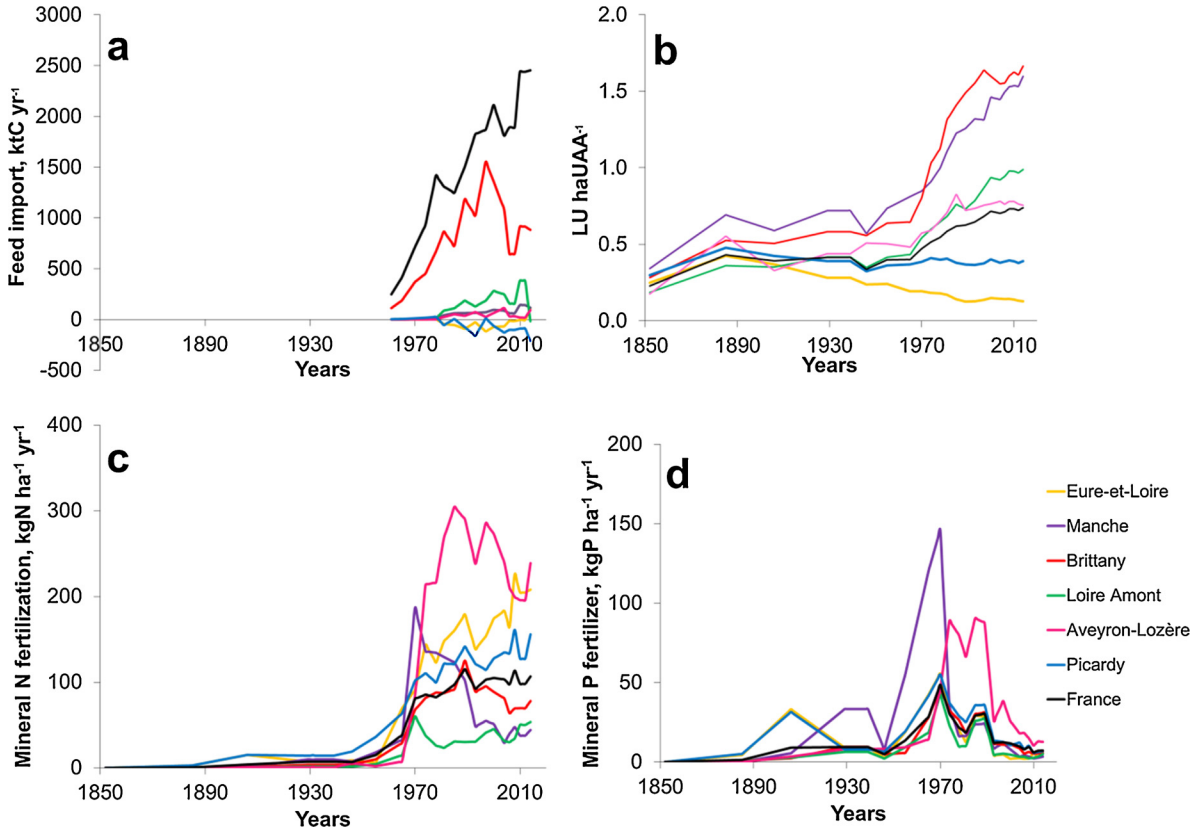

Fig. 3. Evolution of **a** feed importation from abroad, in kt C yr^{-1}; **b** livestock density, in livestock unit (LU) per ha utilized agricultural area (UAA); **c** rates of mineral N fertilization to cropland, in kg N ha^{-1} yr^{-1}; **d** rates of mineral P fertilization to cropland, in kg P ha^{-1} yr^{-1}, for the period from 1852 to 2014 in France and for six typical French territories: Eure-et-Loire, Manche, Brittany, Loire Amont, Aveyron-Lozère, and Picardy. Data were taken from different sources already gathered by Le Noë et al. (2018) (Agreste, 2017 and Gallica.bnf.fr for livestock density and N and P fertilization prior to 1970; Unifa, 2016 for N and P fertilization from 1970 to 2014; SitraM, 2016 and FAO, 2017 for feed importation).

trajectory of the regions were different, following that of cropland NPP, which was the main driver of humified C inputs. In most regions where temporary grassland and fodder NPP decreased while livestock density and importation of feed were still growing, the rise of humified C input to cropland through manure did not compensate the decline of the inputs through temporary grassland and fodder (e.g. Brittany, Loire Aval, and Manche). In territories where temporary grassland and fodders were replaced by roots and tubers and cereals, humified C inputs to cropland slightly increased or stagnated, being mainly impacted by productivity improvements (e.g. Eure-et-Loire, Picardy, Nord Pas-de-Calais). When livestock density kept rising without a reduction in temporary grassland and fodder NPP, humified C inputs to cropland were still increasing, following the increase in manure input (e.g. Aveyron-Lozère, Loire Amont).

3.3. Changes of SOC in cropland

At the territorial scale, changes of SOC in cropland on a per hectare basis followed the evolution of NPP and the subsequent humified C inputs to cropland (Fig. 5). Therefore, SOC dynamics were mostly determined by the amount of humified C inputs to cropland, with crop residue inputs being the main source. However, in some regions manure input to cropland was also an important factor of SOC dynamics in soil and could explain up to 58% of the labile SOC pool changes (as in the case of Cantal-Corrèze) over the whole study period.

At the national scale, the rate of C storage in the upper 30-cm cropland soil showed both large regional and temporal variability, as illustrated in Fig. 6. In the period 1885–1900, most regions revealed a relative rate of C storage of around 1–2‰ per year (Fig. 6a), which is in agreement with the slow yield increase of that period. The period from 1955 to 1970 is characterized by a greater increase of the relative rate of C storage in cropland, exceeding 2‰ per year in most French regions (Fig. 6b) and reaching values over 4‰ per year in several regions (e.g. Manche and Calvados-Orne). In a period of rapid yield growth and increased livestock density, these figures are not surprising. By comparison, Poulton et al. (2018) also found significant rates of relative net C storage in the few decades following increased mineral fertilization on experimental plots (around 4–7‰ per year). In the period 2000–2014, net storage at a relative rate of 0–2‰ per year is observed in the areas of specialized cropping systems in the Paris and Aquitaine basins and in the Alsace Plain. However, cropland SOC stocks decreased in the western part of France at a rate of -1.5‰ yr^{-1}, while mountainous regions with integrated crop and livestock farming systems showed the highest relative rates of SOC storage in cropland (around 2–4‰ per year) (Fig. 6c).

Few observation data are available to validate our predictions of SOC dynamics in agricultural regions. Organic carbon measurements in arable soils are gathered since 2002 in the InfoSoil data base (Arrouays et al., 2002). We used these data to calibrate the value of the inert SOC fraction. The labile to total SOC ratio predicted by the model ranges from 18 to 48% according to regions, which is consistent with the few available estimates of this ratio for local studies (Saffih-Hdadi and Mary, 2008; Barré et al., 2016).

Because of the large variability of cropland SOC levels in each region, the measured data available in the Infosol data base are still too recent to provide a robust estimation of their decennial variation trends. Only long term surveys, including conventional and representative agricultural practices, can provide this type of information. Autret et al. (2016) reported a SOC sequestration rate of 1.9 ± 1.7‰ yr^{-1} over the period 1998–2014 in a conventional cropping system in

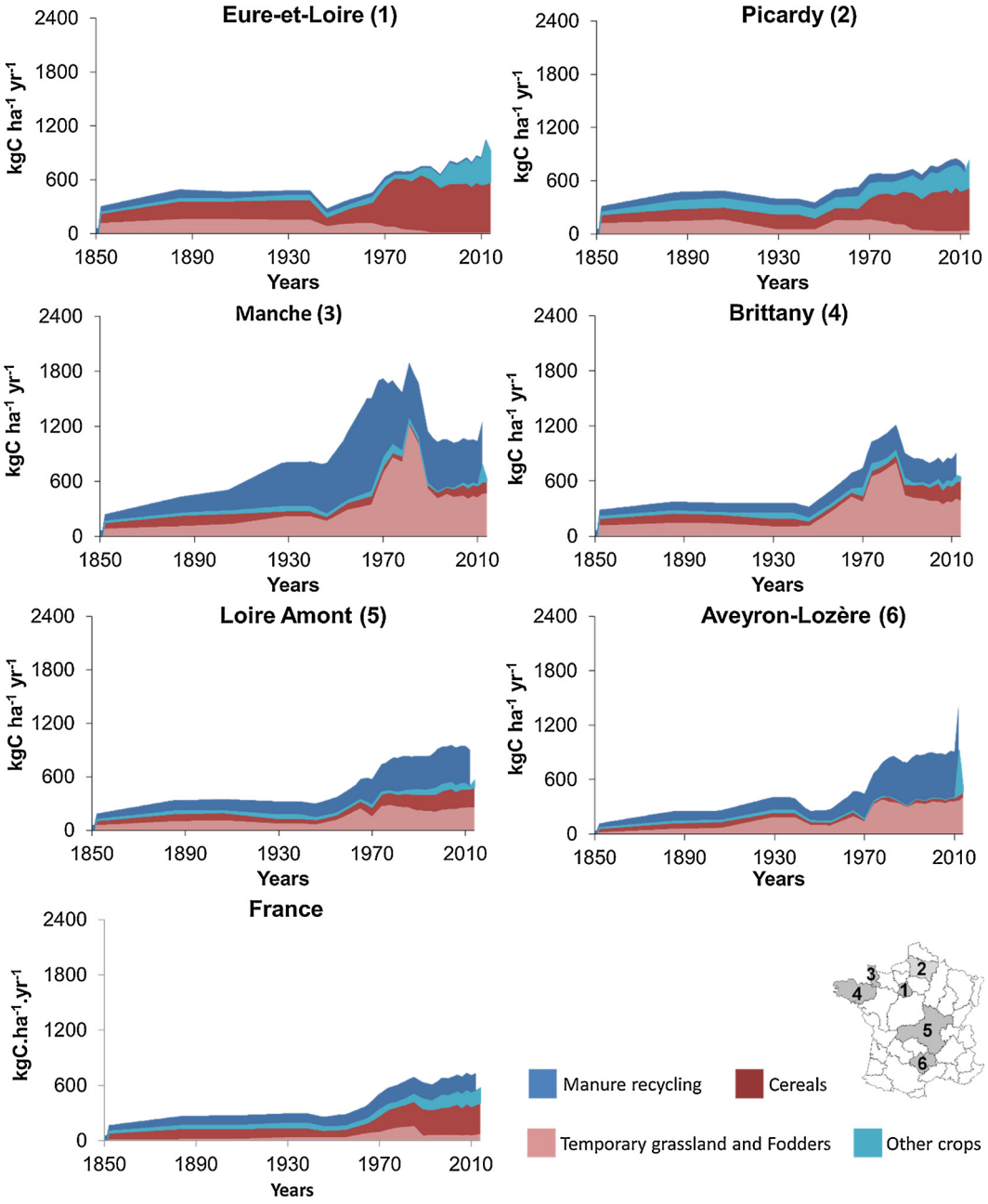

Fig. 4. Evolution of humified C inputs to cropland from 1852 to 2014 in six typical French territories: Eure-et-Loire, Picardy, Manche, Brittany, Loire Amont, and Aveyron-Lozère. Nine categories of inputs are distinguished.

Versailles, representative of the regional agriculture. At Boigneville, also in Ile de France region, Dimassi et al. (2014) reported a mean rate of SOC storage of 1.2 ± 0.2‰ yr^{-1} between 1970 and 2011. This is consistent with our average estimate of 0.7‰ yr^{-1} for the region. In Picardy, a survey of about 400 fields between 1970 and 1997 showed a slight decrease of -0.8 ± 2.5‰ yr^{-1} (Mary and Degrendel, 2002), smaller than our regional estimate of 1.1‰ yr^{-1}. In Brittany, several studies showed net destocking of soil organic matter (e.g. Oehler et al., 2009), supporting our estimate of a negative sequestration rate in this region.

At the national level, cropland SOC stock in the 30 cm top soil on a per hectare basis increased gradually from 1852 to 2014, with the most important gain in the period 1955-1990. This increase is however not directly translated in terms of total SOC stock, because of changes in cropland area. Before 1914, due to the gain of Savoie in 1860, then the loss of Alsace and Lorraine after the 1870 war and its recovery at the end of World War I, the French territory perimeter was not stabilized. After that time, the total cropland area slightly decreased owing to the partly compensating effects of agricultural area reduction by urbanization and reforestation, and increase by grassland conversion into cropland. As a whole, because the drop in cropland area was not compensated by the increased C storage in cropland soils, total SOC stock in Mt C in French cropland is lower in 2014 than it was 1852, although the difference is not significant because of the large associated uncertainties (Table 1).

3.4. Uncertainties

Uncertainties regarding stocks of labile C on a per hectare basis at the end of the model simulation (2014) provide a good approximation of the overall reliability of the numerical results of our study. These uncertainties were estimated on average at 31% but ranged from 13%

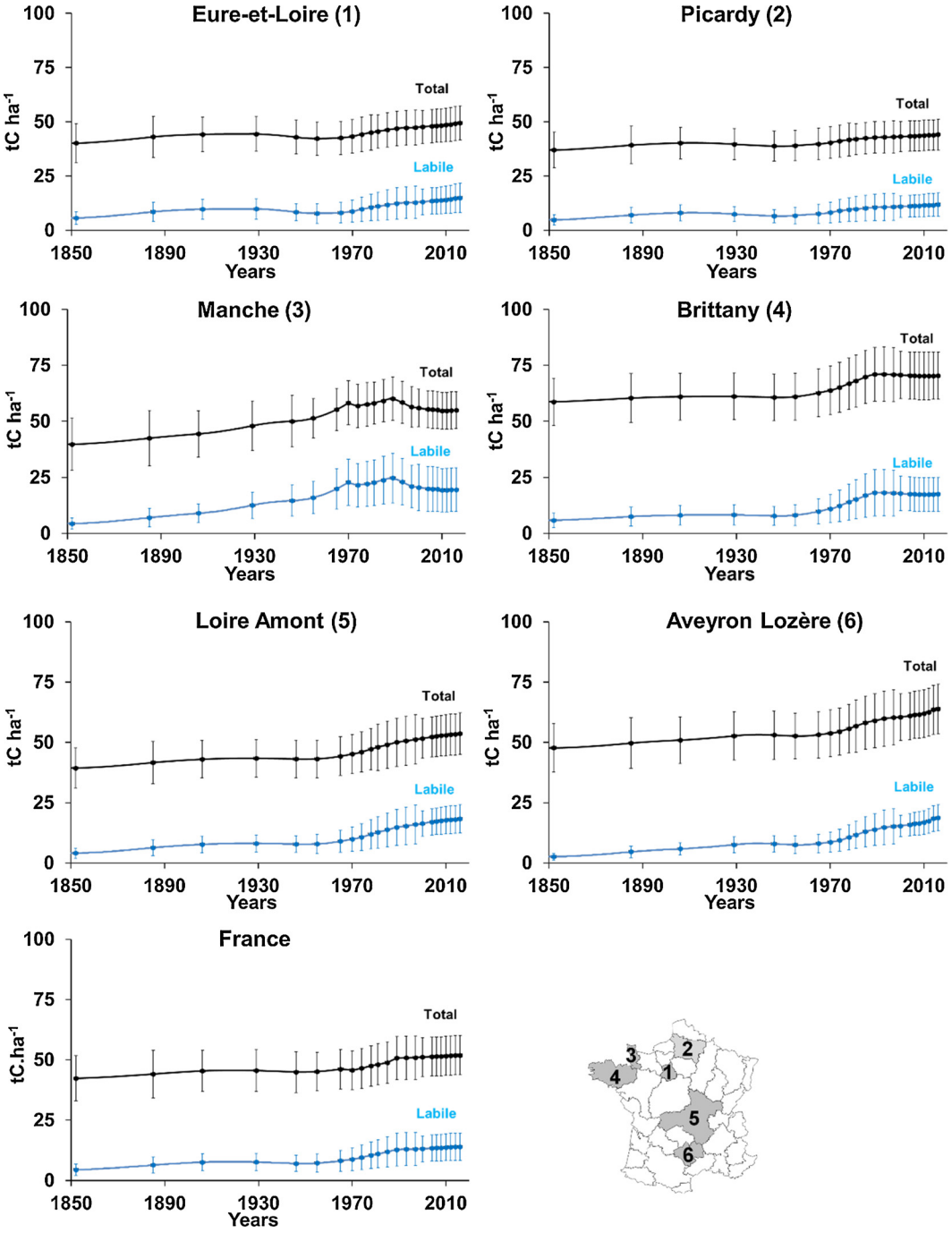

Fig. 5. Evolution of labile and total SOC stocks in the topsoil of cropland (0–30 cm) from 1852 to 2014 in six typical French territories: Eure-et-Loire, Picardy, Manche, Brittany, Loire Amont, and Aveyron-Lozère. Error bars indicate uncertainties as calculated with the Monte Carlo analysis.

in Alpes to 49% in Gironde. This indicates that values of labile SOC stocks estimated should be considered with caution. However, the general trends revealed in this study regarding the SOC evolution in French regions over the last 160 years are likely to be more robust than absolute numbers.

Operational uncertainties in the data and parameters can be estimated through statistical analysis. However, the impact of structural uncertainties concerning the design and hypothesis of the model itself can be more difficult to assess quantitatively. Here the sensitivity analysis performed enabled us to assess the significance of certain variables and key hypotheses (see Fig. 7). At the national level, our analysis indicates that manure inputs to cropland explain 24% of the labile SOC pool change from 1852 to 2014. Contrary to the findings of Aguilera et al. (2018), we found that humified C inputs through weeds played only a minor role in the SOC evolution over the whole study period. According to sensitivity analysis, it explained only 3.7% of labile SOC changes between 1852 and 2014 at the national level. Conversion of permanent grassland to cropland had only minor influence on changes in labile SOC stocks since land-use changes explained 3.4% of SOC stock changes since 1852 at the national level. However, at the territorial level, the conversion from permanent grassland to cropland had an effect on current cropland labile SOC stocks (per hectare basis) ranging from almost 0 in Ile-de-France to 14% in Manche (when compared with the test in which land-use change was not taken into account). Regarding the hypothesis on root-shoot ratio, the labile SOC pool would have been 17% higher in 2014 and 27% lower in 1852 if we

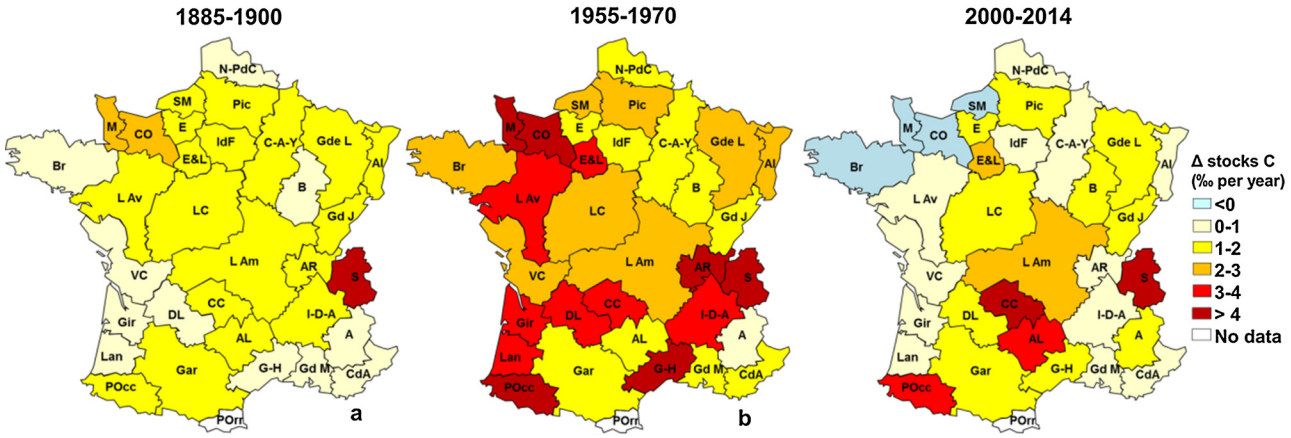

Fig. 6. Maps of relative rates of change in SOC stocks in the topsoil of cropland (0–30 cm) in French territories during the periods **a** 1885–1900, **b** 1955–1970, and **c** 2000–2014. A: Alpes; Al: Alsace; AL: Aveyron-Lozère; AR: Ain-Rhône; B: Bourgogne; Br: Bretagne; C-A-Y: Champagne-Ardennes-Yonne; CC: Cantal-Corrèze; CdA: Côte d'Azur; CO: Calvados-Orne; DL: Dordogne-Lot; E: Eure; E&L: Eure-et-Loire; Gar: Garonne; Gd J: Grand Jura; Gd M: Grand Marseille; Gde L: Grande Lorraine; G-H: Gard-Hérault; Gir: Gironde; I-D-A: Isère-Drôme-Ardèche; IdF: Ile de France; L Am: Loire Amont; L Av: Loire Aval; Lan: Landes; LC: Loire Centrale; M: Manche; N-PdC: Nord Pas-de-Calais; Pic: Picardie; Pocc: Pyrénées Occidentales; POr: Pyrénées Orientales; S: Savoie; VC: Vendée-Charentes.

Table 1
SOC stocks in cropland in France (national scale) in 1852, 1906, 1955, 1990, and 2014.

	Cropland		
	SOC stock t C ha^{-1}	SOC stock Mt C	Area Mha
1852	42 ± 8.0	1100 ± 230	26 ± 2.6
1906	45 ± 7.9	760 ± 140	17 ± 1.7*
1955	45 ± 7.8	850 ± 140	19 ± 1.0
1990	51 ± 8.6	900 ± 150	18 ± 0.9
2014	52 ± 8.1	930 ± 150	18 ± 0.9

± values refer to the results of the Monte Carlo analysis.

* Part of the decrease in cropland area between 1852 and 1906 is related to the loss of part of the Alsace and Lorraine in 1871 following the war against Prussia.

had used a fixed root–shoot ratio instead of a constant but crop-specific root biomass production. Therefore, the hypothesis regarding root biomass production significantly impacted the simulated evolution of a labile SOC pool on the whole study period. Lastly, the sensitivity analysis revealed that accounting for change in temperature led to an 11% lower labile SOC pool at the national level in 2014 when compared with the exploration without temperature change, assuming 1850 values to be constant over the whole study period. This also reveals the impact of climate change over the mineralization of labile SOC.

4. Discussion

4.1. Value of a historical and systemic approach

Our results emphasize that cropland NPP and, to a lesser extent, manure application are the two key determinants of humified C inputs to cropland soils and therefore the main drivers of SOC change on a per hectare basis. This is in line with other studies that highlighted the predominant influence of C inputs on SOC change (e.g. Saffih-Hdadi and Mary, 2008; Virto et al., 2012; Chenu et al., 2014). However, understanding the causes of changes in NPP and manure production requires a systemic and historical perspective that goes beyond pure agronomical determinism. Distinguishing three historical periods can help to identify the changes in agro-food systems that affected NPP and C input to cropland.

In the first period from 1852 to 1950, cropland NPP rose slowly. In most regions, livestock density and NPP evolved in parallel and it can be assumed that the increase in NPP relied on extra-manure inputs. The increase in livestock density was facilitated by an increased share of fodder and temporary grassland in cropland rotation. Such patterns in the evolution of agricultural production have also been identified in other countries for the nineteenth century and the first half of the twentieth century (e.g. Krausmann, 2004). In France, these evolutions were promoted by the growing share of animal protein in human diet (Toutain, 1971), which was permitted by the development of the railway network from 1878 impelled by the Ministry of Public Works

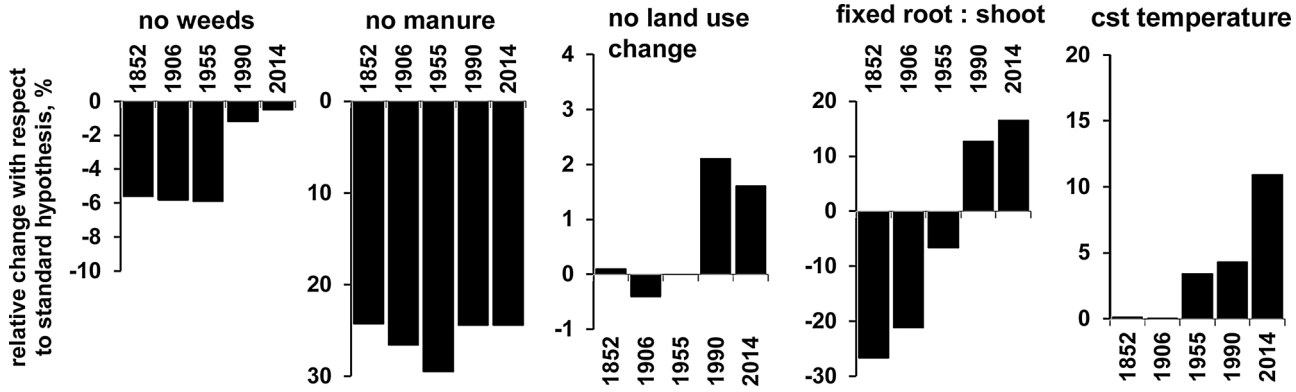

Fig. 7. Relative change (expressed in %) in total SOC stocks in France (national scale) when using one of the five alternative hypotheses (no weeds, no manure, no land-use change, fixed shoot–root ratio and constant temperature since 1852) in 1852, 1906, 1955, 1990, and 2014.

(Freyciney Plan), leading to the opening up of the country-side by the end of the nineteenth century (Duby and Wallon, 1993). However, the rural world in France was largely kept out of the market economy because the agricultural sector was still poorly mechanized and protected from foreign competition by customs barriers implemented from the end of the nineteenth century (Duby and Wallon, 1993). This explains why structural changes in agriculture remained limited at that time in spite of a slight increase in crop yields.

In the second period from 1950 to 1980, cropland NPP rose sharply in all French territories leading to SOC accumulation in soils. This was mainly attributable to an increased use of N and P mineral fertilizer after World War II. With the exception of Ile-de-France, Eure, and Grand Marseille, all regions experienced an increased temporary grassland and fodder NPP, including those with stagnating or even decreasing livestock density (e.g. Picardy and Loire Centrale). Temporary grassland and fodder became the predominant crops in regions with the highest rise in livestock density (e.g. Brittany, Loire Aval, Aveyron-Lozère, and Cantal-Corrèze). This indicates that livestock production was still mostly supported by local crop production. Additional production of temporary grassland and fodder in territories where livestock density did not increase suggests that regional specialization also contributed toward sustaining growing livestock in other regions. However, the national net importation of animal feed from abroad increased from 0.25 to 1.31 Mt C yr^{-1} between 1961 and 1981, which implies that livestock density was also promoted by a higher specialization of agricultural production at the international level. This is line with other studies that emphasized the preeminent role of agricultural trade (Billen et al., 2014; Lassaletta et al., 2014a; Soto et al., 2016; Gonzalez de Molina et al., 2017) and the shift from an organic and solar-based energy system to a mineral and fossil-dependent system at the turn of the 1960s (Krausmann et al., 2008; Carmo et al., 2017; Niedertschneider et al., 2017); this led to the transformation of agro-food systems at various scales from local to global over the course of the last six decades. These trends toward increased regional specialization, crop productivity, mineral fertilizer application rates, livestock density, and feed trade should not be considered as spontaneous rural dynamics. They took place, in their early stage, in the very special context of the Cold War and the "Glorious Thirties" with a strong economic growth, the development of mass consumption, and the technological innovation race in the Western capitalist block. As previously discussed by Le Noë et al. (2018) for the specific case of France, the boost of agricultural productivity was an active state policy fostered at the European and international level through the Monnet (1945) and Marshall (1947) plans (Duby and Wallon, 1978) and supported by a new generation of farmers organized into unions and other movements, which took active part in the modernization of agriculture and its increased connection with upstream (fertilizer and mechanization) and downstream (distribution channel) production chains of what was to become the agri-food industry (Muller, 1984; Duby and Wallon, 1978). Thus, the project of agriculture modernization was not only led by the French state and the European Economic Community (EEC) but also by agricultural organizations themselves such as the *Fédération nationale des syndicats d'exploitants agricoles* (FNSEA, National federation of farmer unions), the *Centre d'Etude Techniques Agricoles* (CETA, Center for agricultural technical studies), *Groupe de Vulgarisation Agricole* (GVA, Agricultural Advisory Group) and the *Jeunesse Agricole Catholique* (JAC, Catholic Agricultural Youth) (Gerbaux and Muller, 1984). As emphasized by Jollivet (2007), these changes clearly turned peasants into entrepreneurs.

A third period from 1980 to 2014 can be identified with the clear emergence of diverging trends in terms of NPP, C inputs to soils, and SOC change. The common feature of this period for almost all regions was the drastic diminution in temporary grassland and fodder NPP. First, in regions with important livestock density such as Brittany, Loire Aval, and Manche this loss in NPP was not fully compensated by other crops and the increase in inputs of manure did not offset the diminution of humified C inputs from temporary grassland and fodder. As a consequence, SOC stocks in cropland started to gradually decline. Specifically in Brittany and Loire Aval where this occurred together with a drop in permanent grassland area and production, livestock nutrition relied increasingly on feed imports from foreign countries, mainly from Latin America (Le Noë et al., 2017). These structural characteristics of the agro-food system of these regions can thus be seen as being responsible for cropland becoming a source of C emission to the atmosphere. The case of Manche, however, is different since permanent grassland production could provide a significant share of animal feed; therefore, importation remained low. The diminishing temporary grassland and fodder NPP that led to the huge simulated loss in cropland SOC in Manche after 1980 appears to be the result of a de-intensification of cropland production (as seen from the reduction in mineral fertilization rate). Second, in stockless regions such as Picardy and Eure-et Loire, where the reduction of temporary grassland and fodder NPP was concomitant with increased cereals, roots, and tuber NPP, an ever-decreasing livestock density and the growing importation of animal feed at the national level may have challenged the outlet of local fodder production owing to the lack of local demand and the concurrence of foreign imports on the national market. In these regions, SOC stocks were stagnating. A third type of trajectory occurred in regions that had rising livestock density, constant or growing temporary grassland and fodder NPP, low importation of animal feed, and increasing or stagnating SOC stocks. Most of these regions could be characterized as integrated crop and livestock farming systems. Changes observed in this period occurred in the context of French and European policy interventionism being considerably diminished, with the lowering of custom barriers, giving way to more liberal governance (Bureau and Thoyer, 2014). While the previous period (1950–1980) had promoted modernization and specialization of agricultural production by the protection of the European market and an active policy of direct aid to increase production, the gradual weakening of this policy in fact lead to the reinforcement of the openness and specialization which had been previously established. This trend of exacerbated specialization of regional agricultural production has also been observed in Spain with adverse effect on the energy return on investment (Guzman et al., 2018), increased greenhouse gas emissions (Lassaletta et al., 2014b), and loss of food sovereignty (Soto et al., 2016). All these changes occurred in the new global historical context following the fall of the communist bloc; the interventionist policies characterizing the former period became obsolete and left the field open to a hegemonic neoliberalism, as made clear in the Washington Consensus in 1990 (Plihon, 2012).

Our analysis thus highlights the need for a systemic and historical approach to better understand the chain of causalities determining the changes in SOC stocks, as illustrated in the simplified representation of Fig. S3.

4.2. Realism and significance of the 4‰ objective

The value of a historical perspective also lies in an improved ability to embrace the future. Based on our results and in the context of the 4 ‰ initiative, the question can be raised of the realism of this objective. Our first estimations showed that, when pooling all territories together at the national level, the rate of C storage in cropland currently leveled off at around 1‰ per year, although regional disparities were found to be important (Fig. 6c). Therefore, in most regions, the 4‰ objective could only be achieved by a considerable increase in C inputs. A recent study performed at INRA (Pellerin et al., 2013) examined possible measures that could increase C inputs and storage. Among these opportunities were: (1) the introduction of cover crops and buffer strips in cropping systems; (2) agroforestry development; and (3) increasing the duration of temporary grassland. Our results indicate that management practices are intrinsically linked to the structure of agro-food systems at the regional scale (Fig. 7). Therefore, we suggest that switching from

specialized agro-food system, either in stockless crop farming or in specialized livestock farming, to integrated crop and livestock farming would foster soil C storage by: (1) raising permanent grassland areas with respect to cropland areas and (2) increasing C inputs to cropland through manure and residues from fodder and temporary grassland production, while decreasing reliance on feed import and N and P mineral fertilizers owing to enhanced nutrients recycling.

Furthermore, the increasing rate of C storage in agricultural soil to 4 ‰ yr^{-1} should be compared with the whole C budget of current agro-food system production. In this regard, the C stored in cropland soil through increased NPP in French regions over the course of the period 1852–2014 should be seen as a side effect of increasing reliance on fossil fuel that provided direct (e.g. tractor) or indirect (fertilizer manufacture) energy to foster NPP. This phenomenon has already been described by several authors as a "fossil-fuel-powered carbon sink" (Gingrich et al., 2007; Erb et al., 2007). Following this view, the increase in SOC in croplands of French regions during 1852–2014 would be only one aspect of the transition from an agrarian to a highly industrialized socioecological regime (Fisher-Kowalski and Haberl, 2007) with a shift from a territory-dependent and solar-based energy system to an extra-territorial, fossil-fuel-based energy system. In the case of France, direct fossil fuel consumption by tractors and building heating represents 5.0 Mtoe yr^{-1} (Mt oil equivalent yr^{-1}) while indirect consumption, including fertilizer production, amounts to 5.4 Mtoe yr^{-1} (Doublet, 2011). If we consider a conversion factor of 0.85 t C toe^{-1}, the C emission due to technical energy consumption of the agricultural sector in France reaches a value as high as 8.8 Mt C yr^{-1}. Therefore, our estimation of total SOC storage in the 30-cm top layer of about 1.7 Mt C yr^{-1} (average of the last 20 years for French cropland) is more than fivefold lower than the current rate of CO_2 emission by the agricultural sector alone.

Such an analysis contradicts the statement of Lal (2016, p. 24) in a recent article: *"The 4 per thousand proposal should be more about the concept than any specific number. The concept that soils and agriculture are solutions to the global issue of Climate change, food insecurity and environmental pollution, is a major shift of historical significance."* Although we may agree with the 4‰ concept, we are not convinced by such possible compensatory remedial measures, which could only be a temporary stopgap of climate change as underlined by several authors (Sommer and Bossio, 2014; Lassaletta and Aguiliera, 2015; Baveye et al., 2018; Poulton et al., 2018).

5. Conclusion

Although statistical models have already been used to predict the future long term trajectory of French cropland SOC under climate change (Meersmans et al., 2016), our work is the first application of a process-based model of soil C dynamics applied at the scale of the whole of France on the long term. Our results stressed that in most French regions, cropland SOC stocks per unit of area have increased from 1852 to 2014, although a decrease was observed in some regions during the last 30 years. These changes mostly depended on NPP and the subsequent C inputs to soil. Different patterns of agricultural production could be identified across time and space within a general great increase of NPP from 1950 to 1980. In this period, changes toward intensification and specialization were permitted by an increased reliance on fossil fuel energy for fertilizer production and agricultural mechanization but also contributed to the global emission of CO_2 and climate perturbation. The technical and structural evolution of French territories toward agriculture intensification and specialization during this period responded to national and international political will and economic interests. This transition period was characterized in all regions by a significant increase of SOC stocks in cropland. During the most recent decades, the different trajectories followed by regional agricultural systems in France resulted in either a reduction or a stabilization of cropland SOC stocks. C sequestration in soil is far from compensating the direct and indirect CO_2 emissions by the agricultural sector.

Overall, we showed that in countries such as France where a sharp increase in cropland NPP had already occurred, further accumulation of C at a rate as high as 4‰ is unlikely to be reached. In the short term, land-use planning increasing permanent grassland areas and agro-ecological practices favoring increased C inputs to soil could enable some additional C sequestration. However, in the medium and long term the sustainability of agricultural production with regard to C emission mitigation will also depend on how the energy metabolism and agro-food systems can be reconfigured according to the well-being and environmental requirements of the human population.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.envsci.2018.12.027.

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